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Use of wastes as option for the mitigation of CO_2 emissions in the Brazilian power sector

Luciano Basto Oliveira [a], Rachel Martins Henriques [a], Amaro Olimpio Pereira Jr. [b,*]

[a] Virtual Institute of Climate Change (IVIG/COPPE/UFRJ), Caixa Postal 68565, CEP 21945-970, Ilha do Fundão, Rio de Janeiro, Brazil
[b] Center for Integrated Studies of the Environment and Climate Change (CentroClima/COPPE/UFRJ), Caixa Postal 68565, CEP 21945-970, Ilha do Fundão, Rio de Janeiro, Brazil

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ABSTRACT

The present study presents an analysis of the options available for the mitigation of CO_2 emissions in the Brazilian power sector. The objective is to verify the potential use of wastes for electrical energy generation and its competitiveness in comparison with other sources of renewable energy. A comparison was made using marginal abatement cost curves derived from a reference scenario obtained from earlier studies dealing with the expansion of the Brazilian power sector. The results showed that the availability of wastes is significant and that they can be used at a cost 20–60% lower than that of wind power generation, a subsidized source of energy in Brazil. It can therefore be concluded that it would be more efficient if incentives were applied to the use of wastes for electrical power generation since it offers socio-environmental benefits which go far beyond the reduction of CO_2 emissions.

Contents

1. Introduction

Brazil enjoys a wide variety of climate conditions and the planet's greatest biodiversity. These characteristics bring the country considerable advantage in terms of availability of renewable natural resources, allowing the energy sector in general, and the electrical in particular, to have much lower emissions rates compared with the rest of the world (see [15]).

Various studies, however, such as that of the EPE (Brazilian Bureau of Energy Studies, 2007) [3], the International Energy Agency [8], the European Commission [4] and the study prepared for UNEP by the Center for Integrated Studies of the Environment and Climate Change–CentroClima/COPPE/UFRJ [10], show that electricity consumption will increase at a rate superior to 3% per year until 2030, which will require the current installed capacity to be increased by 100 GW. Such expansion will demand that the country seizes upon all available sources to guarantee this supply for the population.

Having this in mind and taking a long term perspective, various courses of action are open to meet the growing demand for electrical energy. Should Brazil decide to maintain the current high hydroelectric participation in the electric sector it will need to increase the supply from the North, a region of high potential but also of great environmental sensitivity. If it is decided to expand fossil fuel use considerable investment will be required in coal, natural gas and petroleum extraction as well as processing. In this case the country would be failing to make full use of its advantage in having a generating system with predominance of renewable sources. There is, moreover, the possibility of an increase in the nuclear program which also requires considerable financial investment, both in R&D and in infrastructure, in uranium prospection and processing and in

* Corresponding author. Tel.: +55 21 3512 3182; fax: +55 21 3512 3199.
E-mail address: amaro@ppe.ufrj.br (A.O. Pereira Jr.).

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power plant construction. Furthermore Brazil can invest more in renewable sources, also of ample availability in the country, but whose technology is not as advanced as the previously cited sources.

The country has been showing signs of serious commitment to the maintenance of a significant participation of renewable in its energy matrix as demonstrated by incentives given to such sources, among which are prominent the Program of Incentives for Alternative Energy Sources (PROINFA) and renewable energy purchase and sale auctions. Small hydroelectric, sugar cane bagasse, and wind power plants are among the sources favored by such incentives.

It can be noted that, despite all these initiatives, there is significant penetration of fossil fuel sources, which, while on the one hand offer the guarantee of supply at moderate prices, on the other significantly increase the greenhouse gas (GHG) emissions of the Brazilian electricity sector.

The country has also given signs of active participation in the battle against global warming. The Federal Government recently launched the National Plan on Climate Change (PNMC), to promote internal actions to mitigate greenhouse gas emissions without prejudicing the well-being of the population. Among the aims of the PNMC (which served as basis for law no. 12187 of 29th December 2009, establishing national policy for climate change) is that of maintaining the high participation of renewable energy in the electrical matrix, thereby preserving Brazil's prominent position in the international context.

With this in mind, the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) has made the issue of new environmental licenses for thermal power plants conditional upon the latter compensating for their CO_2 emissions through reforestation, and, when more advantageous, through providing 2/3 of the generation from renewable sources or through energy efficiency. Such demands open new opportunities for generation from wastes which, in spite of the country-wide potential, have only benefited from incentives offered by the clean development mechanism (CDM).

The aim of this article is thus to demonstrate the existence of a great potential for generation from wastes at environmentally competitive costs compared with other renewable sources, an alternative which has not been sufficiently taken into account in expansion studies carried out in the country. The analysis used marginal abatement cost curves developed from the reference scenario in "Development First: Linking Energy and Emission Policies with Sustainable Development", the study carried out by La Rovere et al. [10] in the context of the Development First project.

2. Reference scenario

The study used as reference scenario had as objective the identification of paths and actions for development in the great emergent economies which would allow for the obtaining of positive climatic results and facilitate dialogue between national and international level decision makers, entrepreneurs, and the scientific community. The project was financed by UNEP and had the participation of Risoe Centre and other organizations of note in China, India and South Africa.

In the elaboration of the Brazilian scenarios the following assumptions, among others, were taken into account:

- Brazilian GDP: a 4% average annual growth rate is considered.
- Population: a 1.09% average growth rate is assumed.
- Hydroelectric potential: of the 230,000 MW total available potential the use of 191 GW was considered. The coming into operation of the Belo Monte Hydro Power Plant was also assumed, with half capacity (5500 MW) in 2010 and the other half in 2015.
- Nuclear: The Angra III Power Plant was assumed to come into operation in 2014, taking into account the date of its approval by the National Council of Energy Policy (CNPE). The possibility of expansion of this segment with two more Nuclear Power Plants of 1000 MW capacity each was also taken into account.

Table 1
Generating capacity (GW).

Year	Coal	Oil	Natural gas	Hydro	Nuclear	Biomass	Wind	Total
2005	1.42	1.43	9.00	76.70	1.97	1.44	0.65	92.60
2010	2.42	1.43	13.50	78.74	1.97	6.44	0.65	105.15
2015	2.42	1.43	17.50	95.13	1.97	10.44	1.35	130.23
2020	2.42	1.93	18.00	121.60	3.31	13.44	1.85	162.55
2025	3.42	1.93	20.00	150.06	3.31	13.44	2.85	195.01
2030	3.42	2.43	22.00	169.82	3.31	15.44	2.85	219.27

Source: [10].

A reference scenario for the Brazilian power sector was simulated including this data and using the MESSAGE model (Model for Energy Supply System Alternatives and their General Environmental impacts) originally developed at IIASA (International Institute for Applied System Analysis) for the optimization of an energetic system. The IAEA acquired the latest version of the model and various updates have been carried out, especially with the introduction of a user-friendly interface to facilitate its operation.

The result, showing the potential expansion of the power sector, is presented in Table 1 where the "Hydro" column includes small hydro.

Given the differences in capacity factors, the energy available for each source is presented in the following Table 2.

The scenario results show that the renewable sources in Brazil are competitive. The potential for small hydro and sugar cane bagasse is virtually exhausted. There is also a significant expansion in the larger scale hydroelectric plant sector due to major projects entering in to operation during the coming years. The nuclear expansion is limited to Angra III, the third national nuclear plant, whose construction has already begun. Wind power generation is virtually restricted to the North Eastern region where the potential is greatest. Finally, the expansion of generation is basically boosted by plants using natural gas, a fuel whose participation in the Brazilian energy mix has increased considerably.

GHG emissions were calculated using the IPCC methodology. The results are presented in Table 3, expressed in CO_2 equivalents.

For the purpose of comparison and verification of the accuracy of the results, these have been matched with those of other studies carried out during the same period, as shown in Table 4, where "Other Technology" includes nuclear and other renewable sources.

It must be pointed out that the EPE (Brazilian Bureau of Energy Studies) study, the "National Energy Plan" (PNE) 2030 [3], assumed an annual economic growth rate of 4.1%, close to that used in the

Table 2
Electricity generation (TWh).

Year	Coal	Oil	Natural gas	Hydro	Nuclear	Biomass	Wind	Total
2005	8.68	5.01	47.32	369.53	13.78	8.45	1.71	454.48
2010	14.84	5.01	70.96	379.38	13.78	37.80	1.71	523.47
2015	14.84	5.01	91.98	458.32	13.78	61.27	3.55	648.75
2020	14.84	6.76	94.61	585.88	23.20	78.88	4.86	809.04
2025	20.97	6.76	105.12	723.01	23.20	78.88	7.49	965.43
2030	20.97	8.51	115.63	818.21	23.20	90.62	7.49	1.084.64

Source: [10].

Table 3
CO_2 emissions ($MtCO_2$).

Year	Calo	Oil	Natural gas	Total CO_2
2005	9.71	4.46	21.29	35.46
2010	16.61	4.46	31.93	53.00
2015	16.61	4.46	41.39	62.46
2020	16.61	6.02	42.57	65.20
2025	23.47	6.02	47.30	76.79
2030	23.47	7.58	52.03	83.09

Source: [10].

Table 4
Comparison of results (GW) – 2030.

Technology	Development first [10]	PNE [3]	WEO [8]	WETO [4]
Hydro	169.82	156.3	128.12	114.00
Natural gas	22.00	21.03	11.50	53.00
Oil	2.43	5.50	12.00	4.00
Coal	3.42	6.01	–	10.00
Other	21.60	36.08	28.38	24.00
Total	219.27	224.9	180.00	205.00

Source: [3,4,8,10].

"Development First" study [10], which was of 4%. The expansion presented in the PNE only considers the system connected to the grid, differently from the Development First study, with PNE linking in all isolated system at the final horizon of the study. The studies of the International Energy Agency (IEA), the "World Energy Outlook" (WEO) [8], and the European Commission's "World Energy Technology Outlook" (WETO) 2050 [4], assume that the Brazilian economy will grow only 3% per year until 2030. This accounts for the lower expansion compared with PNE and Development First.

3. Alternative scenarios

The reference scenario option was to propose a breakthrough in the energy usage of biomass wastes, both rural and urban, by virtue of their own merits or by means of government incentives which, in fact, have not been granted. These wastes have not succeeded in advancing as an energy source in the country, in spite of their immediate offer, ease of mensuration, availability during most of the year – all year round in the case of the urban – and, in some cases, the existence of a processing cost linked to the final destination, which could result in negative cost.

The data used therefore is of estimated potential offer and cost, national sources being always preferred due to their greater reliability for immediate deployment.

As regards urban wastes, the National Basic Sanitation Survey of the Brazilian Institute of Geography and Statistics (IBGE) [6] and the National Information System on Sanitation [17], were taken as basis; to these were applied IBGE's [7] expected demographic growth rates for the period in question, the correlation between GDP per capita and waste production, as well as an expected growth in GDP in the horizon under analysis similar to that used in the reference scenario.

The only technology considered for urban waste was dry anaerobic digestion of the organic fraction [14], by virtue of being that which allows the greatest obtainment of carbon credits, its operation being neutral in GHG emissions [11]. This technology produces biogas – used in an internal combustion motor, at an electric conversion efficiency rate of the order of 30% – and simultaneously achieves the highest recycling rate for packing materials (idem). Although this solution is not the best in terms of exclusive electricity generation [12], association with the energy saving provided by the recycling achieves the greatest possible amount of available energy [16]. From the financial point of view, the combination results in energy efficiency gains and related carbon credits, thus reducing the cost of the electricity (idem).

Table 5
Electrical potential and estimated cost of the sources analyzed.

Product	Cost (US$/MWh)	TWh				
		2010	2015	2020	2025	2030
SUW	273	4.4	5.0	5.7	6.5	7.5
Sewage	182	3.1	3.9	4.8	6.0	7.3
Agricultural	50.3	450.1	543.7	645.8	756.8	867.9
Cattle	75.5	23.0	26.0	31.0	36.0	42.0

Source: Elaborated by the authors based on [1–3,5–7,14].

In the case of sewage, a technological combination was analyzed which involves the use of biogas generated in sewage sludge digesters, of oil produced in the pyrolysis of sewage sludge, and of biodiesel resulting from the esterification of the fats present in the foam; an internal combustion engine can be used for all the fuels, or a turbine for the biogas, processed to turn it equivalent to natural gas for the purpose of increasing efficiency [13].

The energy potential of the agricultural wastes was calculated applying PNE 2030 data on soybean and corn wastes offer [3] to the parameters of the technology considered for these products, the Rankine cycle combustion, with an electric conversion efficiency rate of 20%, similar to that used for sugar cane.

In the case of animal waste, the national herd [6] was taken into account and extrapolated using the growth rate proposed by FAPRI [5], but using only the portion confined to stables – dairy cattle in the case of bovine herds. The production of manure and of biogas emissions resulting from its decomposition was based on Brazilian Enterprise of Agropecuary Research [2] data. Here the technology used is that of a biogas digester where the gas is destined for an internal combustion motor, with an electric conversion efficiency rate of 30%, with costs similar to those of the firms which won the Parana Energy Company (COPEL) [1] tender.

The energy potential of the cultivated biomass wastes thus reaches the values presented in Table 5 which follows, where typical commercial tariffs are also shown.

From a comparison of Tables 2 and 5 it can be deduced that the potential of agricultural wastes is superior to the fossil fuels offer foreseen in the reference scenario, which prevented the use of it in its entirety in the time horizon – even though this source can substitute others, non emitters of greenhouse effect gases and more costly.

Two criteria were adopted to measure the environmental benefits of the substitution of electricity: for the renewable sources present in the reference scenario which are competitive with the others and, for this reason, use up all available offer in the study horizon (bagasse and small hydro), for the quantities there determined, the average emission factor was used, calculated as the ratio between the emissions and the electricity in each year; for the other sources, the emission avoided was effectively that of the fossil fuel substituted by wastes. This differentiation allows the demonstration of policies already implemented and of new proposals.

4. Marginal abatement cost curve

As already shown, the alternative scenarios are constructed based on the assumption that all the generating potential provided by the sources analyzed is used during the time horizon of the present study. Such energy substitutes that which originates from fossil sources by order of the respective average generating costs. The first generating source to be substituted is thus oil, then coal, and finally natural gas. The average generating cost in coal fired

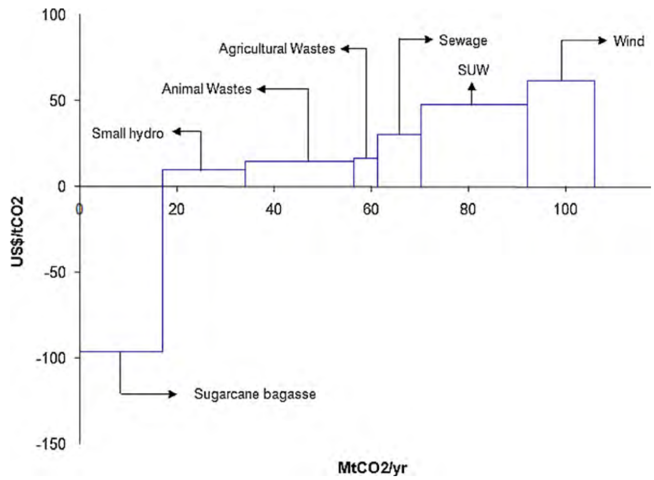

Fig. 1. Marginal abatement cost curve.

factories in Brazil is higher than in gas fired factories since the national mineral has low calorific value and a high level of impurities, while transport costs make the imported mineral, of better quality, more expensive. In fact the importation of coal for electricity generation can only be made viable by the strategic location of the ports where the factories are situated (or are to be built).

The marginal abatement cost curve is thus built comparing the generating cost and the reduction in CO_2 emissions in the alternative scenario with those in the reference scenario, taking into account, using IPCC methodology, the benefits of direct energy substitution and of the mitigation of methane emissions resulting from its recuperation and energy conversion. The negative values demonstrate the economic viability of the measure from the usual cost benefit point of view. The positive values show that they require a mechanism, such as a policy or a specific program (such as CDM), to make them viable.

The result of the analyses are presented in Fig. 1, which follows, where the abscissas axis represents the annual abatement level and the ordinate axis the cost per t of mitigated CO_2. The sources are shown in order of abatement cost.

From Fig. 1 above it is observed that the increase in use of sugar cane bagasse and small hydro in the reference scenario was correct from the point of view of abatement cost since these are the cheapest sources. The participation of wind power is only justified in this scenario because of the lack of other sources and of the increase of the participation of renewable sources to maintain the level and meet the National Plan of Climate Change.

In the alternative scenario it is observed that there are energy products capable of meeting the electricity demand of the system connected to the grid, attending the security criteria, and reducing environmental effects related to CO_2 emission mitigation, as wind energy does, but at costs between 20% and 60% less.

In this case, considering that the technologies for usage of residual agricultural biomass (virtually identical to sugar cane bagasse), of animal waste and urban organic wastes, which are basically constituted of biodigesters associated with generating groups, do not require technological development, or even imported technological input, the only technical restriction to the implantation of thermoelectric plants capable of using such materials would be the in the capacity to supply such equipment, a factor which could limit progress in this usage.

It is thus seen that the offer of incentives for the utilization of the Brazilian wind power potential neglects sources which could achieve the same aims at lesser cost; this despite the fact that such offer is motivated by the desire to increase the efficiency of the system connected to the grid, to avoid GHG emissions, and to stimulate the development of a national technology for a source available for exploitation in various parts of the planet.

Furthermore, the mobilization of the agents for the use of residual biomass could make of Brazil an exporter of the excess of this fuel, thus meeting international demand, estimated by Junginger [9] to be between 48 and 1200 EJ in 2050, when the EPE [3] estimate of the national offer, of agricultural wastes alone, is of 15 EJ; the principal trading routes of this international demand are shown in Fig. 2 below.

5. Concluding remarks

The present study has attempted to demonstrate the existence of a great potential for the use of wastes for power generation at competitive prices when compared with other renewable sources.

It is observed that Brazil has given signs of commitment to fighting climate change and for this reason has, through PROINFA and specific alternate energy source auctions, created conditions for the introduction of less polluting technologies in the national electricity sector.

The technologies which have benefited from incentives are small hydro, bagasse and wind power generation. The first two are competitive with conventional technologies. The wind power is the exception, requiring special conditions to be viable.

It has been shown, however, that such incentives would be more efficient if applied to the use of wastes for power generation since these offer mitigation cost reductions of between 20% and 60%, and socio-environmental benefits reaching far beyond the reduction of CO_2 emissions.

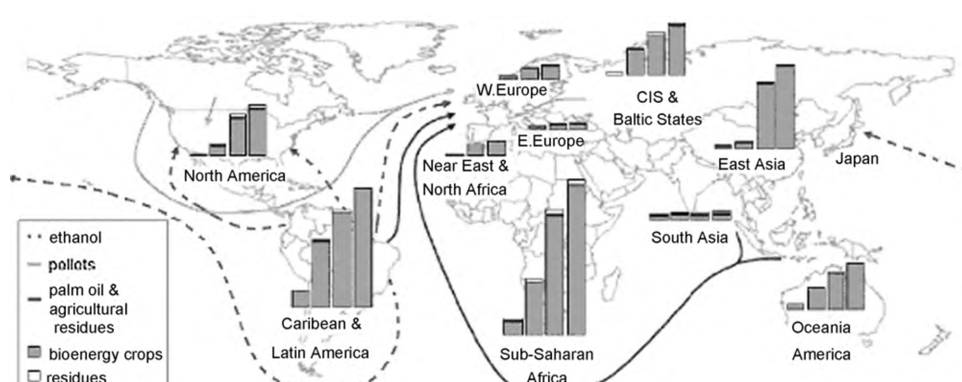

Fig. 2. Bioenergy trade – going global.*Source*: adapted from IEA [8].

References

[1] COPEL – Companhia Paranaense de Energia. Processo de compra de energia de fonte biodigestora a biogás oriundo de DEJETOS; 2009 Available at:http://www.copel.com/hpcopel/root/sitearquivos2.nsf/arquivos/resultado_biogas/$FILE/VENCEDORES_biogas27_01_09.pdf.
[2] EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária. Limitações e vantagens do uso de farinhas de origem animal na alimentação de suínos e de aves. In: 2° Simpósio Brasileiro Alltech da Indústria de Alimentação Animal; 2005 Available at:http://www.cnpsa.embrapa.br/sgc/sgc_arquivos/palestras_r2v84s4u.pdf.
[3] EPE – Empresa de Pesquisa Energética. Plano Nacional de Energia (PNE) 2030. Brasil: Ministério de Minas e Energia – MME; 2007.
[4] European Commission. World energy technology outlook 2050 (WETO-H2); 2006.
[5] FAPRI. U.S. and world agricultural outlook 2009. In: FAPRI staff report 09-FSR 1. Iowa, USA: Food and Agricultural Policy Research Institute, Iowa State University/University of Missouri-Columbia; 2009 Available at:http://www.fapri.iastate.edu/outlook/2009/text/OutlookPub2009.pdf.
[6] IBGE. Censo Agropecuário 2003; 2000 Available at:http://biblioteca.ibge.gov.br.
[7] IBGE. Estimativas de Projeções de População até 2050, 2008; 2009 Accessed in 2009. Available at:ftp://ftp.ibge.gov.br/Estimativas_Projecoes_Populacao/Revisao_2008_Projecoes_1980_2050/Revisao_2008_Projecoes_1980_2050/.
[8] IEA. World Energy Outlook 2030. International Energy Agency 2007.
[9] Junginger M. Sustainability criteria for bioenergy products derived from forest biomass. In: 2nd symposium on forest biomass and processing residues for energy production; 2008.
[10] La Rovere EL, Pereira Jr AO, Simões AF, Pereira AS, Dubeux CBS, Costa RC, et al. Development first: linking energy and emission policies with sustainable development for Brazil. New Delhi: UNEP – United Nations Environment Programme/Risoe Centre; 2007, 88 pp..
[11] Oliveira LB. Potencial de aproveitamento energético de lixo e de biodiesel de insumos residuais no Brasil. Ph.D. Thesis. Universidade Federal do Rio de Janeiro; 2004.
[12] Oliveira LB, Rosa LP. Brazilian waste potential: energy, environmental, social and economic benefits. Energy Policy 2003;31(14):1481–91.
[13] Oliveira LB, Fagundes MVM. Estacões de Tratamento de Esgoto com Produtores Independentes de Energia. In: X Congresso Brasileiro de Energia; 2004.
[14] OWS – Organic Waste System. Digestão Anaeróbica Seca; 2009 Available at:http://www.ows.be.
[15] Pereira Jr AO, Soares JB, Oliveira RG, Queiroz RP. Energy in Brazil: toward the sustainable development? Energy Policy 2008;36(1):73–83.
[16] Pimenteira CAP, Pereira AS, Oliveira LB, Rosa LP, Reis MM, Henriques RM. Energy conservation and CO_2 emission reductions due to recycling in Brazil. Waste Management 2004;24:889–97.
[17] SNIS – Sistema Nacional de Informações sobre Saneamento; 2008. Available at: http://www.snis.gov.br.